RESEARCH PAPER

EVALUATION OF NEW RELEASE GLOBAL GEOPOTENTIAL MODEL (GGMS) OVER EAST MALAYSIA

Noorhurul A. Othman[1], Muhammad F. Pa'suya[1*], Ami H. Md Din[2], Mohamad A. Che Aziz[1], Nurul S. Hazelin Noor Azmin[1], Mohd A. Abd Samad[1], Mohd A. Abdullah[3]

[1] Environment and Climate Change Research Group (ECC), Collage of Built Environment, Universiti Teknologi MARA, Perlis Branch, Arau Campus, 02600 Arau, Perlis, Malaysia

[2] Geospatial Imaging and Information Research Group (GI2RG), Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia

[3] UO Geomatics Resources Sdn. Bhd, No. 306A, Jalan Sungai Korok, Alor Setar, 05400 Alor Setar, Kedah, Malaysia

***Corresponding author:** faiz524@uitm.edu.my

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ABSTRACT. Global Geopotential Model (GGM) is a mathematical representation of the Earth's gravity field and geoid, which is developed to provide accurate information about the variations in the Earth's gravitational potential across the entire globe. Recently numerous organizations and research centres have developed multi GGMs derived from several types of available gravity and height datasets to estimate orthometric heights from GNSS measurements. In this study, we present an accuracy evaluation and assessment of the nineteen recent and popular GGMS using actual GNSS/levelling points, and gravity anomaly points. The goal of this research is to find the optimum model for the study area which is located in the East Malaysia for further determination of geoid modelling in the regional scale. The selection of these areas basically is due to their renowned for uncontrolled topography and various datums. The results indicate that for geoid undulation, the XGM2019e_2159 with value of 0.195 model is the best fit GGM for the estimation model for East Malaysia. For gravity anomalies, the most reliable GGM for the study area is GO_CONS_GCF_2_DIR_R5 with RMSE of 32.456

KEYWORDS: sGlobal Geopotential Models (GGMs), GNSS Levelling, East Malaysia

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INTRODUCTION

The geoid is a surface which the gravitational potential is uniform, and it is corresponds to a continuous sea level across the globe. It serves as the precise reference for height measurement and physically represents the Earth's shape (Perdana and Heliani, 2017). Nowadays, the ultimate goal of geodesist is to produce 1cm accuracy of local geoid model. However, it has yet been realised for most of the areas around the world. This is only possible with the optimal usage of all available data and methods. Various methods and approach in geoid determination have been introduced by different groups, such as Least Square Modification of Stokes' Formula (Sjöberg, 2003a, 2003b), Curtin University of Technology's (CUT) method (Goyal et al. 2019), Remove Compute-Restore (RCR) method (Schwarz et al. 1990), UNB Stokes-Helmert method (Ellmann and Vaníček. 2007), etc. Each method has different philosophy and steps in geoid computation but all those methods use similar input data which are Global Geopotential Model (GGMs). This data become the crucial input in the geoid computation as they provide essential long-wavelength information combined with Stokes' integration over local gravity data collected from terrestrial measurements. Notably, advancements in satellite gravity missions, such as Gravity Recovery and Climate Experiment 9GRACE) (Tapley et al. 2003; Tapley et al. 2005) and Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) (Pail et al. 2011) have substantially improve our understanding of the global gravity field, particularly in the long-wavelength bands (Bruinsma et al. 2013; Brockman et al. 2014) are now available to the scientific community through public domain resources at (http://icgem.gfz-potsdam.de/ICGEM).

Global Geopotential Models (GGMs) are mathematical representation of Earth's gravitational potential achieved through a spherical harmonic expansion. These models employ fully normalised Stokes' coefficients (C_{nm} and S_{nm}) for each degree (n) and order (m) to characterise the gravitational potential. These coefficients enable the derivation of various Earth-related parameters, including geoid undulation, normal gravity, gravity anomaly, vertical deflection, and gravity disturbance (Mainville et al. 1992). GGMs can be categorised into three main types: satellite-only models, combined models, and tailored models (Rapp et al. 1997; Chen et al. 2022). For satellite-only GGMs, the coefficients are derived by analysing the orbital deviations of satellites, such as those collected during missions like CHAMP, GRACE, and GOCE. However, the accuracy and resolution of these models are limited due to their low degree. Meanwhile the combined models are created by merging gravity data from various sources, including satellites, terrestrial gravity measurements, airborne gravity data, and satellite altimeter data in marine regions. As a result, these models achieve higher degrees and provide more accurate results compared to satellite-only models. Tailored GGMs are a product of enhanced GGMs harmonic coefficients using specialised mathematical techniques found within the first and second groups. These models are primarily designed to elevate the degree of accuracy within the models.

Prior to the geoid computation, the crucial step is to identify the optimal GGM that fit to the local geometrical vertical datum and gravity field data (Amos and Featherstone 2003; Benahmed 2010; Ellmann 2010; Strykowski and Forsberg 2010; Doganalp 2016; Saari and Bilker 2018). This selection process is imperative because the published error metrics associated with GGMs cannot be readily applied to assess their performance in a specific region, as they may be overly optimistic or represent global averages. Therefore, it is crucial for users to evaluate the GGMs to ensure their applicability for geoid computations in their target regions (Kiamehr and Sjöberg 2005)

Based on the literature records, there are numerous published studies investigated the accuracy of the GGMs in their interest regions using various methods and approaches, for example see Doganalp (2016), Al Shouny et al (2023), Alemu (2023), Al-Othman et al. (2016) and El-Ashquer et al (2016), etc. One of the most frequently employed methods to determine the best GGM for an area's gravity field is to compare GGMs through independent datasets of GNSS levelling (e.g., Yilmaz et al, 2016; Lee et al. 2020; Goyal et al. 2019)), terrestrial gravity anomalies (e.g., Hirt et al. 2011; Alemu 2021; Alemu 2023), and both (e.g., El-Ashquer et al. 2016; Benahmed, 2010, Guimarães et al.2012; Al Shouny et al. 2023). The main objective of this study is to identify the optimal GGMs that align with the characteristics of East Malaysia, a crucial step for subsequent geoid determination in this specific region. Consequently, we have selected a total of nineteen (19) GGMs released between 2014 and 2022 for evaluation. This evaluation is based on comparisons with a geometrical geoid derived from GNSS levelling, free air anomalies obtained from terrestrial gravity measurements, and a local precise gravimetric geoid model.

STUDY AREA

The study area is located in East Malaysia, encompasses of -3° N ≤ Latitude ≤ 9.75° N, 108° E ≤ Longitude ≤ 120.75° E, as illustrated in Fig. 1. The total land area within this study region spans approximately 198,447 square kilometers. It is further divided into two states namely Sabah in the northern region and Sarawak in the southern region.

SOURCES OF DATA

In this study, the performances of the nineteen (19) selected GGMs have been assessed using three datasets, which are GNSS levelling derived geoid height, terrestrial gravity anomalies, and official gravimetric geoid over East Malaysia obtained from the Department of Survey and Mapping Malaysia (DSMM). These datasets are crucial to evaluate the accuracy of the GGMs in East Malaysia. The details of the data are as follows:

GNSS Levelling

In total, 53 observation points have been generously provided by the DSMM. The spatial distribution of these observation points is illustrated in Fig. 2(a). However, since the levelling datum over the Sarawak region is referenced to the three different datums, 30 points over this state area have been excluded in the evaluation process to avoid any inconsistencies caused by the different datums. The GNSS levelling data was collected through a GNSS field campaign by DSMM from October to December 2016 with a minimum of 12 hours of observation period (Jamil et al. 2017) and processed using Bernese software.

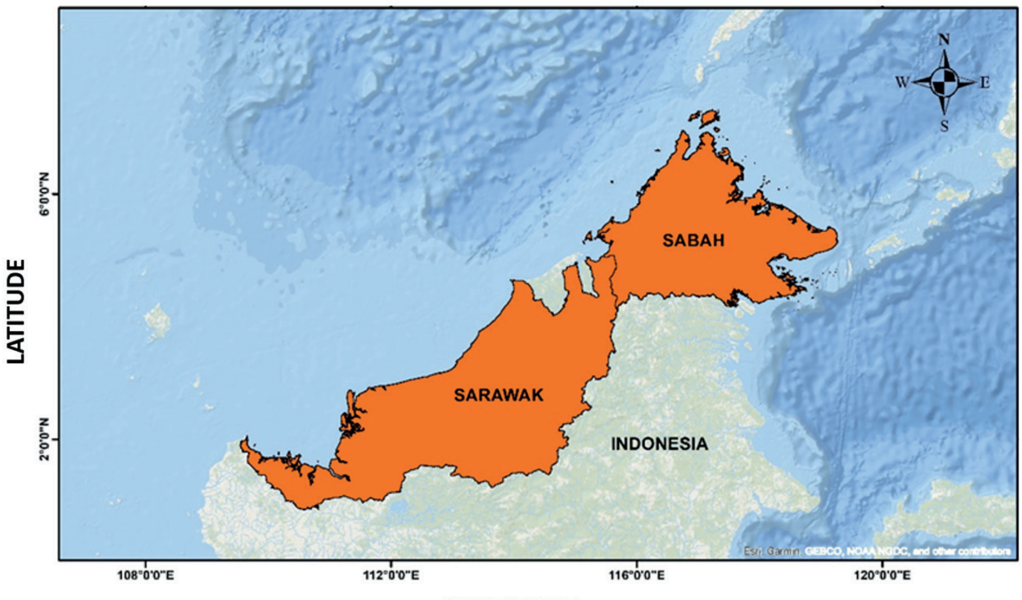


Fig. 1. Study area over East Malaysia

Terrestrial Gravity anomalies

In the second method of evaluation, a comparison has been conducted between all the selected GGMs and the terrestrial gravity anomalies, Δg_{FA}. These gravity anomalies have been computed using data collected from 690 terrestrial gravity measurement points across East Malaysia. The distribution of these terrestrial gravity data points is depicted in Fig. 2(b).

LOCAL GRAVIMETRIC GEOID MODEL

The performance assessment of all selected GGMs also includes a comparison with geoid height extracted from precise local gravimetric geoid. This gravimetric geoid was meticulously computed by the DSMM as part of the Marine Geodetic Infrastructure Project (MAGIC). The computation process involves the use of various data sources, including the mixed spherical harmonic model EGM08/GOCE, SRTM digital elevation model, DTU15 satellite altimeter-derived gravity anomalies at sea, and airborne gravity data. Notably, this gravimetric geoid achieves an accuracy level of approximately 3 to 5 cm across most of East Malaysia (Jamil et al. 2017). In this study, the geoid height obtained from each GGM has been compared with the corresponding local gravimetric geoid data at the same grid spacing. Fig. 3 provides a visual representation of the gravimetric geoid over East Malaysia, as provided by DSMM. This comparison is instrumental in assessing the accuracy and suitability of the GGMs' for geoid determination within the East Malaysian region.

GLOBAL GEOPOTENTIAL MODELS (GGMs)

In the fields of science and engineering, improving the understanding of the Earth's gravity field is crucial for precise orbit determination and height measurement systems (Rummel et al. 2002). Achieving a thorough understanding of the Earth's gravity field requires continuous advancements in both accuracy and spatial resolution. GGMs play a crucial role in representing the Earth's gravitational field, particularly in capturing the long-

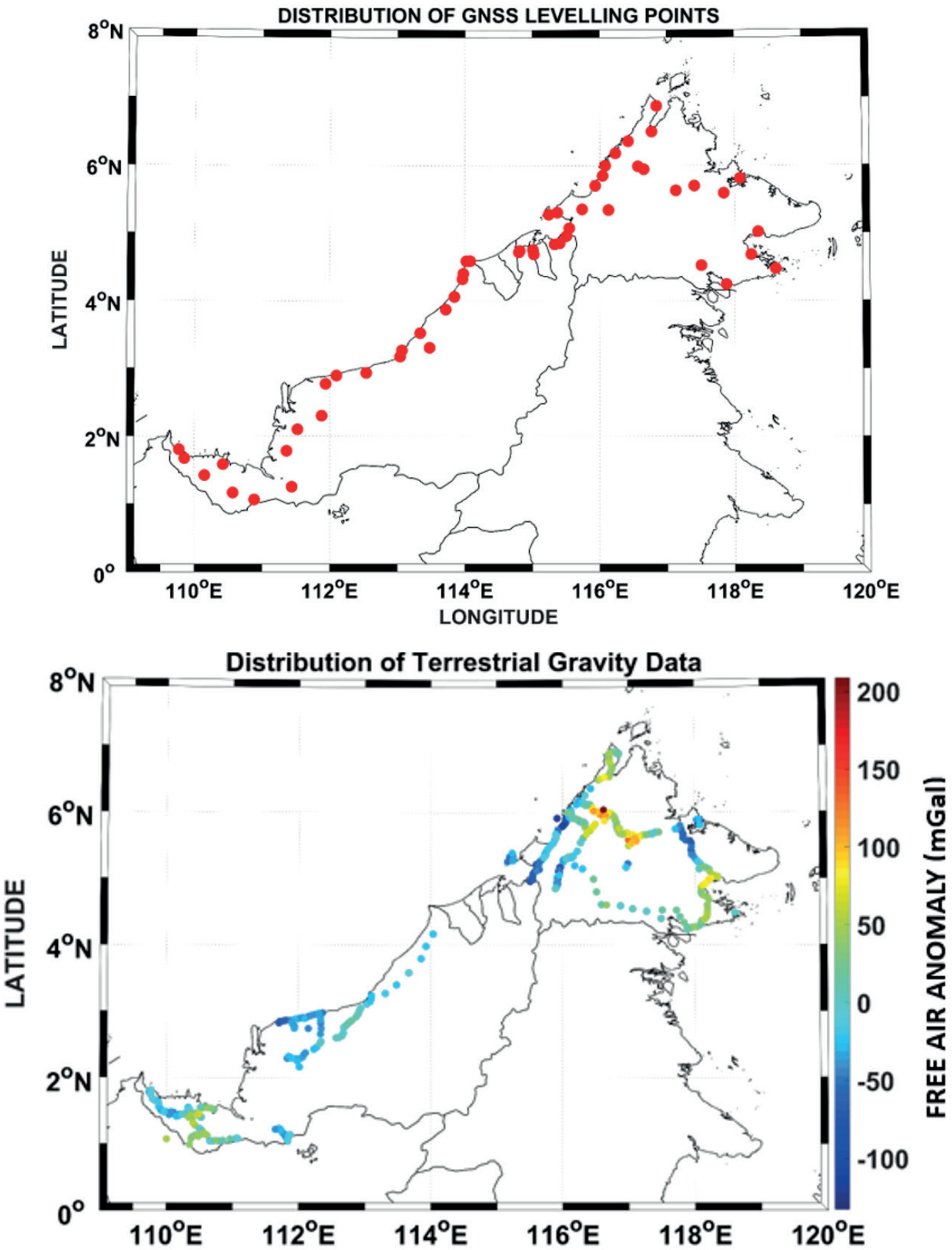


Fig. 2. Study area over East Malaysia

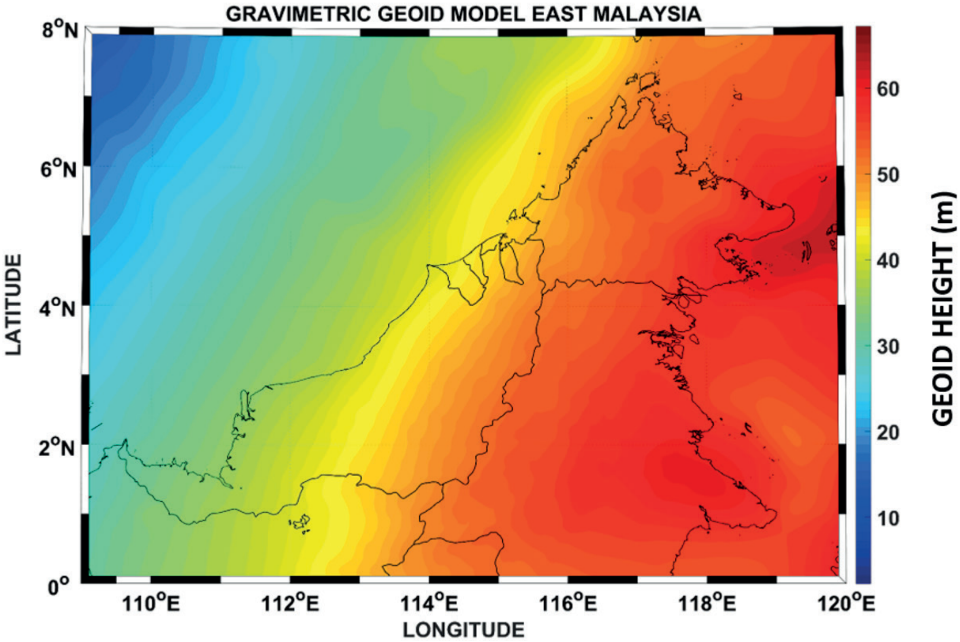


Fig. 3. Local gravimetric geoid model over East Malaysia

wavelength components (Amos and Featherstone, 2003; Kiamehr and Sjöberg, 2005). These models are built using a set of fully normalized spherical harmonic coefficients, which are derived from geopotential solutions (Mainville et al. 1992). The development of GGMs relies on integrating multiple data sources, including satellite observations, terrestrial gravity measurements, marine gravity anomalies from satellite altimetry, and airborne gravity data (Chen et al., 2022; Hirt et al., 2011; Rapp, 1997). Such comprehensive data integration ensures that the models provide an accurate representation of the Earth's gravity field across different spatial scales and environments. In the scope of this study, have conducted an evaluation of 19 GGMs, with four of them being categorized as combination GGMs and the remainder classified as satellite-only GGMs. To the best of our knowledge, no prior research has been conducted specifically addressing GGMs in the context of East Malaysia. Table 1 provides a comprehensive summary of the 19 GGMs evaluated in this study, and the spherical coefficients used were sourced from the ICGEM website (http://icgem.gfz-potsdam.de/tom_longtime) (Barthelmes, 2013). These GGMs, released between 2014 and 2022, encompass a wide range of models, including satellite-only ones (utilizing data from missions like GOCE and/or GRACE) and combined geopotential models. The geoid height (N) derived from these GGMs can be represented using a set of spherical harmonic coefficients, as described in equation (Rummel et al. 2002).

$$N_{GM} = \frac{GM}{\gamma r}\sum_{n=o}^{n_{max}}\left(\frac{R}{r}\right)\sum_{m=0}^{n} P_{nm}(\cos\theta)\left(C_{nm}\cos m\lambda + S_{nm}\sin m\lambda\right) \quad (1)$$

where θ, λ, and r are the point's co-latitude, longitude, and geocentric radius, respectively; R is the reference ellipsoid's major axis radius; GM is created by multiplying the Earth's mass by the gravitational constant; γ is the reference ellipsoid's mean gravity; C_{nm} and S_{nm} are the series development Stokes coefficients; P_{nm} n-degree and m-order representation of the associated Legendre functions. Meanwhile, the gravity anomaly derived from GGMs up to spherical harmonic degree n_{max} can be calculated with the following equation (Heiskanen et al. 1967).

$$\Delta g_{GM} = \frac{GM}{r^2}\sum_{n=0}^{n_{max}}\left(\frac{R}{r}\right)(n-1)\times\sum_{m=0}^{n} P_{nm}(\cos\theta)\left(C_{nm}\cos m\lambda + S_{nm}\sin m\lambda\right) \quad (2)$$

DATA PROCESSING

The evaluation of the GGMS in this study was conducted using two distinct sets of data which is GNSS levelling and terrestrial gravity anomalies dataset. The GGM geoid heights and gravity anomalies were computed using the MATLAB based software EGMlab which developed by Kiamehr and Eshagh (2008), from the Division of Geodesy at the Royal Institute of Technology in Stockholm, Sweden. For the consistency of the comparison and minimize biases due to differences in reference ellipsoid, tide conventions and geoid reference, all the GGMs used are in the Tide-Free system and use GRS80 as the normal field. In the first evaluation, the GGMs gravity anomalies was compared with the 690 terrestrial gravity points. Prior to the comparison, the gravity data have been processed to compute free air anomalies, Δg_{FA} with the following equation:

$$\Delta g_{FA} = g + F - y_0 \quad (3)$$

where g is gravity value on the topographic surface, F is the free-air correction (approximately 0.3086H), H is the orthometric height and γ_0 is the normal gravity on the GRS80 ellipsoidal surface which can be computed using the Somigliana Formula as follows:

$$\gamma_o = \gamma_e \frac{1 + k\sin^2\varphi}{\sqrt{\left(1 - e^2\sin^2\varphi\right)}} \quad (4)$$

$$k = \frac{b\gamma_P - a\gamma_e}{a\gamma_e} \quad (5)$$

where γ_e is the gravity on the equator, γ_p is the gravity at the pole, b is the semi-major axis of the ellipsoid, e is the semi-minor axis of the ellipsoid, e is the first eccentricity and φ is the geodetic latitude. In order to analyse the performance of each GGMs, a basic statistical analysis was performed by calculating the Mean Error (ME) and Root-Mean Square Error (RMSE) by comparing the GGM gravity anomalies, Δg_{GCM} and terrestrial gravity anomalies, Δg_{FA} as follows:

$$\Delta g = \Delta g_{GCM} - \Delta g_{FA} \quad (6)$$

Table 1. Global Geopotential Models that are evaluated in this paper (S: Satellite, G: Gravity, A: Altimetry)

Model	Year	Max Degree	Data Source	Reference
SGG-UGM-2	2020	2190	A, EGM2008, S(Goce), S(Grace)	Liang et al. 2020
XGM2019	2019	2190	A,G, S(GOCO06s), T	Zingerle et al. 2019
SGG-UGM-1	2018	2159	EGM2008, S(Goce)	Xu et al. 2017
GECO	2015	2190	EGM2008, S(Goce)	Gilardoni et al. 2016
TONGJI-GMMG2021S	2022	300	S (Goce), S (Grace)	Chen et al. 2022
GO_CONS_GCF_2_TIM_R6e	2019	300	G(Polar), S(Goce)	Zingerle et al. 2019
GO_CONS_GCF_2_TIM_R6	2019	300	S(Goce)	Brockmann et al. 2021
GO_CONS_GCF_2_DIR_R6	2019	300	S	Bruinsma et al. 2014
TONGJI-GRACE02K	2018	180	S(Grace)	Chen et al, 2018
GOSG01S	2018	220	S(Goce)	Xu et al. 2017
IfE_GOCE05s	2017	250	S	Wu et al, 2017
GO_CONS_GCF_2_SPW_R5	2017	330	S(Goce)	Gatti et al, 2016
Tongji-Grace02s	2017	180	S(Grace)	Chen et al, 2016
ITU_GGC16	2016	280	S(Goce), S(Grace)	Akyilmaz, et al, 2016
GO_CONS_GCF_2_SPW_R4	2014	280	S(Goce)	Gatti et al, 2014
GO_CONS_GCF_2_TIM_R5	2014	280	S(Goce)	Brockmann et al, 2014
GO_CONS_GCF_2_DIR_R5	2014	300	S(Goce), S(Grace), S(Lageos)	Bruinsma et al, 2013
JYY_GOCE04S	2014	230	S(Goce)	Yi et al, 2013
GOGRA04S	2014	230	S(Goce), S(Grace)	Yi et al, 2013

The ME and RMSE are computed by using following equations:

$$ME = \frac{\sum_{i=1}^{n} N_{GCM} - h - H_{MSL}}{n} \quad (7)$$

$$RMSE = \sqrt{\frac{\left(\sum_{i=1}^{n}\left(N_{GCM} - h - H_{MSL}\right)\right)^2}{n}} \quad (8)$$

In the second comparison, the GGMs geoid height, N_{GCM} have been compared with the geometrical geoid from GNSS levelling, $N_{GNSS\ levelling}$ as follows:

$$N_{GNSS\ levelling} = h - H_{MSL} \quad (9)$$

$$\Delta N = N_{GCM} - N_{GNSS\ levelling} \quad (10)$$

where the h and H_{MSL} is the ellipsoidal height and mean sea level height at the benchmark. Subsequently, ME and RMSE of the difference were computed using Equation (6) and (7). The same procedure also be implemented to compare the GGMs geoid height and local gravimetric geoid. Notably, the comparison between GNSS levelling and GGMs derived geoid height may be influenced by several errors including the datum inconsistencies (Yilmaz et al. 2016; Goyal et al. 2019), the commission and omission errors of the GGMs as well as the biases /errors introduced by GNSS and levelling (Ssengendo 2015). Thus, to minimize the effect of all the systematic biases, the absolute differences have been fitted using a 4-parameter model based on:

$$\Delta N_i = a_i^T x + v_i \quad (11)$$

$$a_i = \left[1 \cos\varphi_i \cos\lambda_i \sin\lambda_i \sin\varphi_i\right]^T \quad (12)$$

$$x = \left[x_1 x_2 x_3 x_4\right]^T \quad (13)$$

where, a_i and x is a vector of unknown parameters and known coefficients, respectively. Details of the strategy of GGMs evaluation is illustrated in the Fig. 4.

RESULTS AND ANALYSIS

In this section, the results of the comparison are summarized in Tables 2 and 3 for the GNSS levelling and terrestrial gravity anomaly datasets, respectively. Each GGM listed was evaluated up to its maximum available degree and order. The computations were conducted point by point, with the GGM-derived gravity field values determined at the geocentric latitude and longitude corresponding to each observation point. Based on the statistical analysis of the comparison with geometrical geoid height, as presented in Table 2, the XGM2019e-2159 GGM model emerges as the best fit with GNSS levelling data among the combined GGMs, with a ME of 0.530 meters and a RMSE of 0.195 meters. This result aligns closely with an earlier study by Tocho et al. (2022), which reported an accuracy of approximately 0.219 meters for the XGM2019e-2159 model. However, the GECO GGM model can also be considered a strong contender, as the statistical analysis shows that its RMSE is only slightly different from that of XGM2019e-2159, with ME and RMSE values of

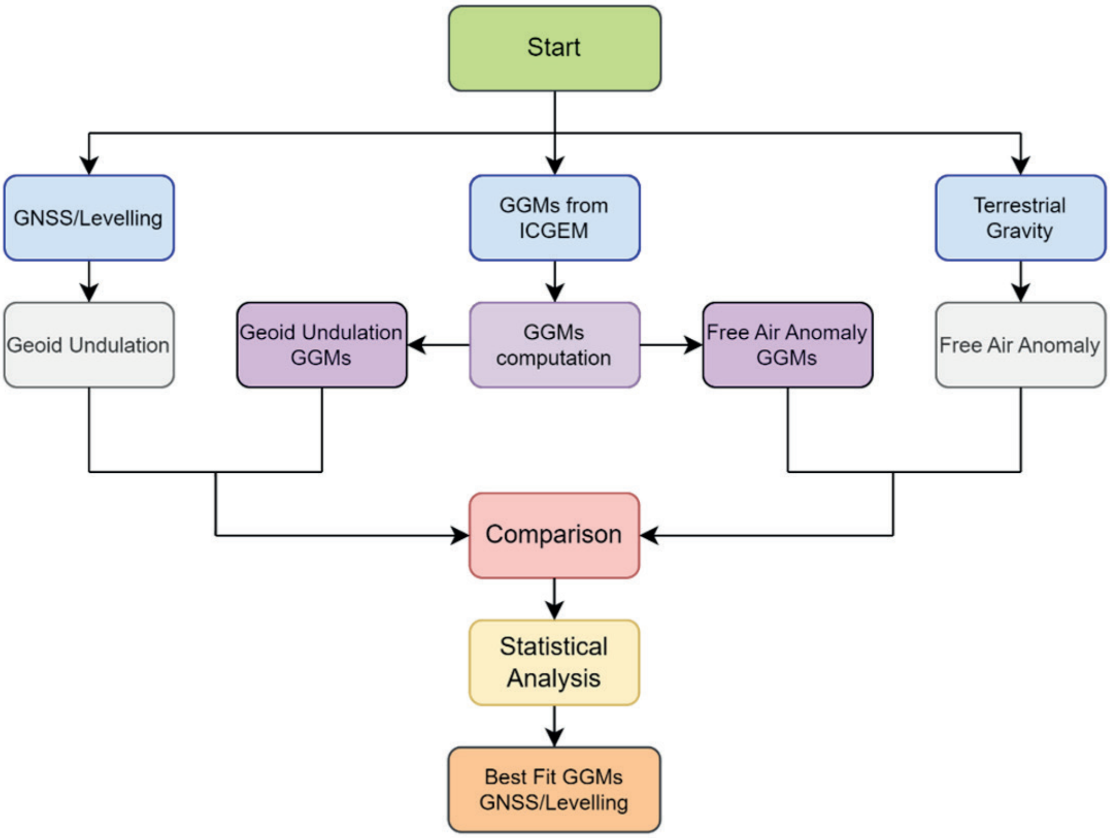


Fig. 4. Methodology of the study

0.525 meters and 0.198 meters, respectively. Additionally, the SGG-UGM-2 and SGG-UGM. -1 models exhibit RMSE values of 0.240 meters and 0.244 meters, respectively. The accuracy of GECO obtained in this study is consistent with the previous studies by Tocho et al. (2022) and Goyal et al. (2019).

Among the satellite-only GGMs, it is evident that the GO_CONS_GCF_2_SPW_R5 model (maximum degree 330) exhibits the best fit with the GNSS levelling data, characterized by a ME of 0.729 meters and a RMSE of 0.209 meters. However, the performance of several GGMs model such as GO_CONS_GCF_2_TIM_R6e, GO_CONS_GCF_2_DIR_R6, GO_CONS_GCF_2_TIM_R5, GO_CONS_GCF_2_TIM_R6, and ITU_GGC16 also show good performance. Statistical analysis shows the RMSE of those models only marginally different from GO_CONS_GCF_2_DIR_R6 which is below than 1cm (in the range of 0.214m–0.217 m). The RMSE of other satellite-only GGM fall in the range of 0.222m to 0.682 with Tongji-Grace02s having the poorest RMSE. The differences (after fitting) between the geoid height from the optimum GGM (XGM2019e-2159 and GO_CONS_GCF_2_SPW_R5) and geometrical geoid height over East Malaysia are illustrated in Figure 6. The range of the different (after fitting) between XGM2019e-2159 GGMs and GNSS levelling falls within the range of 29.112mGal-60.372mGal. Meanwhile, the range of the different (after fitting) for the GO_CONS_GCF_2_SPW_R5 GGM fall within the range of 28.959mGal - 60.644mGal.

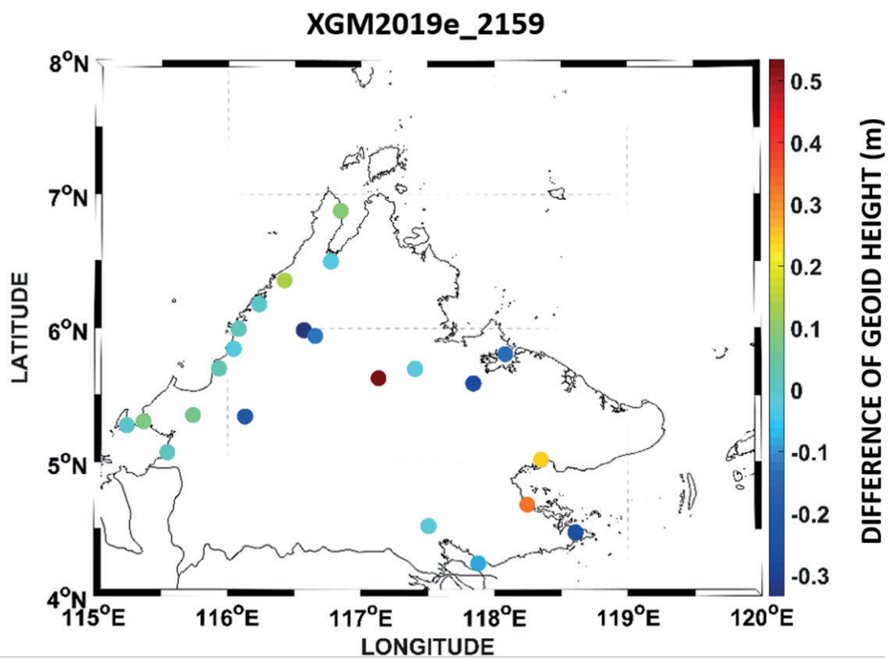
The statistics regarding the differences between terrestrial gravity anomalies and GGMs gravity anomalies are presented in Table 3. From the statistical results, it is observed that the RMSE of the combined GGMs falls within the range of 32.780 mGal to 32.760 mGal. Among these, the GECO GGM model exhibits the best fit with terrestrial gravity anomalies, characterized by a ME of 46.669 mGal and an RMSE of 32.760 mGal. Interestingly, the statistical analysis in this table reveals that the XGM2019e-2159 model has the poorest RMSE (32.780 mGal), compared to the SGG-UGM-1 and SGG-UGM-2 models, which have RMSE values of 32.775 mGal each. However, it's worth noting that the accuracy of the combined GGMs does not exhibit significant differences, with variances of less than 0.01 mGal. Among the satellite-only GGMs, the GO_CONS_GCF_2_DIR_R5 model demonstrates the best agreement with terrestrial gravity anomalies, with an ME of 46.494 mGal and an RMSE of 32.456 mGal, as indicated in Table 3. In contrast, the accuracy of the GO_CONS_GCF_2_SPW_R5 GGM markedly differs from that of the other satellite-only GGMs. The RMSE values for the latter group fall within the range of 32.456mGal to 32.907mGal, with the Tongji-Grace02s model having the poorest RMSE. To visually depict the differences between the gravity anomalies derived from the optimal GGMs (GECO and GO_CONS_GCF_2_DIR_R5) and the geometrical geoid height over East Malaysia, Fig. 8 provides an illustration. Meanwhile Fig.7 display the geoid heights over East Malaysia derived from the GO_CONS_GCF_2_DIR_R5 and GECO GGMs. These illustrations provide insight into the variations in the geoid height across different regions of East Malaysia, indicating how each model represents the Earth's gravity field and the shape of the geoid in the study area. As shown in Fig. 8, the differences between GECO and terrestrial gravity anomalies fall within the range of 29.112 mGal to 60.372 mGal. Meanwhile, the differences between GO_CONS_GCF_2_DIR_R5 and terrestrial gravity anomalies are within the range of 28.959 mGal to -60.644 mGal. Relating to the GECO and GO_CONS_GCF_2_DIR_R5 spike, the sharp deviation a mismatch between the predicted gravity values from the model and the actual terrestrial gravity measurements.

CONCLUSIONS

This study evaluated the performance of GGMs in developing geoid models for East Malaysia by comparing their accuracy against terrestrial gravity anomalies and

Table 2. Statistical analysis of the difference between GGMs and GNSS levelling observations

GGM	Min	Max	Mean	RMSE
SGG-UGM-2	0.000	1.555	0.556	0.240
XGM2019e-2159	**0.175**	**1.583**	**0.530**	**0.195**
SGG-UGM-1	0.016	1.777	0.577	0.244
GECO	0.029	1.546	0.525	0.198
GO_CONS_GCF_2_TIM_R6E	0.184	1.586	0.641	0.217
GO_CONS_GCF_2_DIR_R5	0.187	1.692	0.713	0.230
GO_CONS_GCF_2_DIR_R6	0.208	1.664	0.693	0.213
GO_CONS_GCF_2_SPW_R4	0.024	1.567	0.468	0.260
GO_CONS_GCF_2_SPW_R5	**0.181**	**1.847**	**0.729**	**0.209**
GO_CONS_GCF_2_TIM_R5	0.212	1.625	0.699	0.214
GO_CONS_GCF_2_TIM_R6	0.187	1.579	0.642	0.217
GOGRA04S	0.000	1.843	0.728	0.331
GOSG01S	0.000	2.152	0.531	0.378
IfE_GOCE05s	0.068	2.104	0.742	0.307
ITU_GGC16	0.188	1.549	0.653	0.214
JYY_GOCE04S	0.001	1.980	0.780	0.330
Tongji-GMMG2021S	0.114	1.896	0.732	0.222
Tongji-Grace02k	0.000	4.212	0.891	0.656
Tongji-Grace02s	0.001	4.685	0.966	0.682



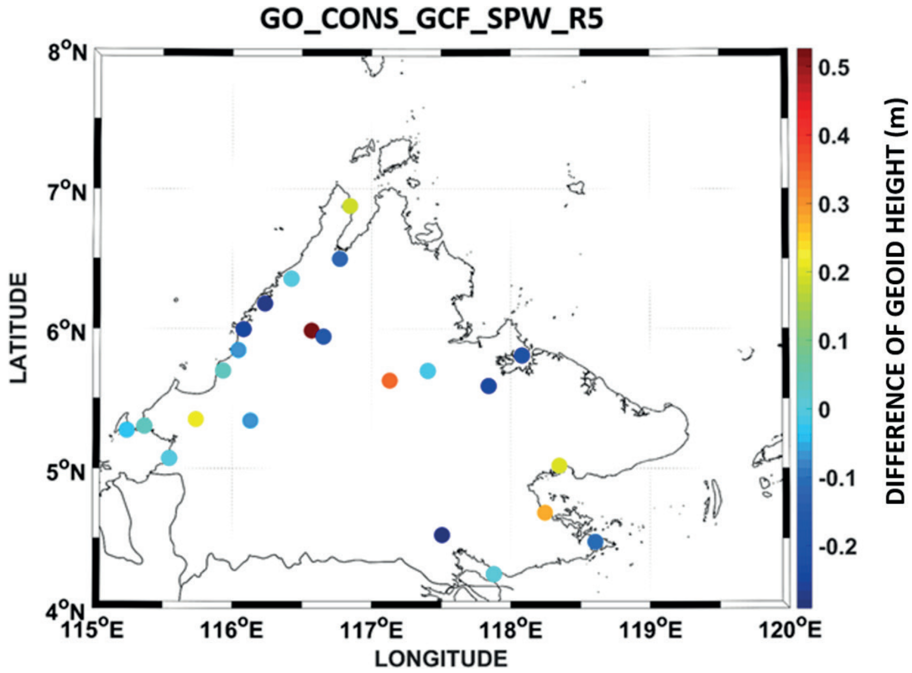


Fig. 5. Differences between (a) XGM2019e_2159 GGM and (b) GO_CONS_GCF_SPW_R5 GGM geoid height with GNSS levelling derived geoid height over Sabah region

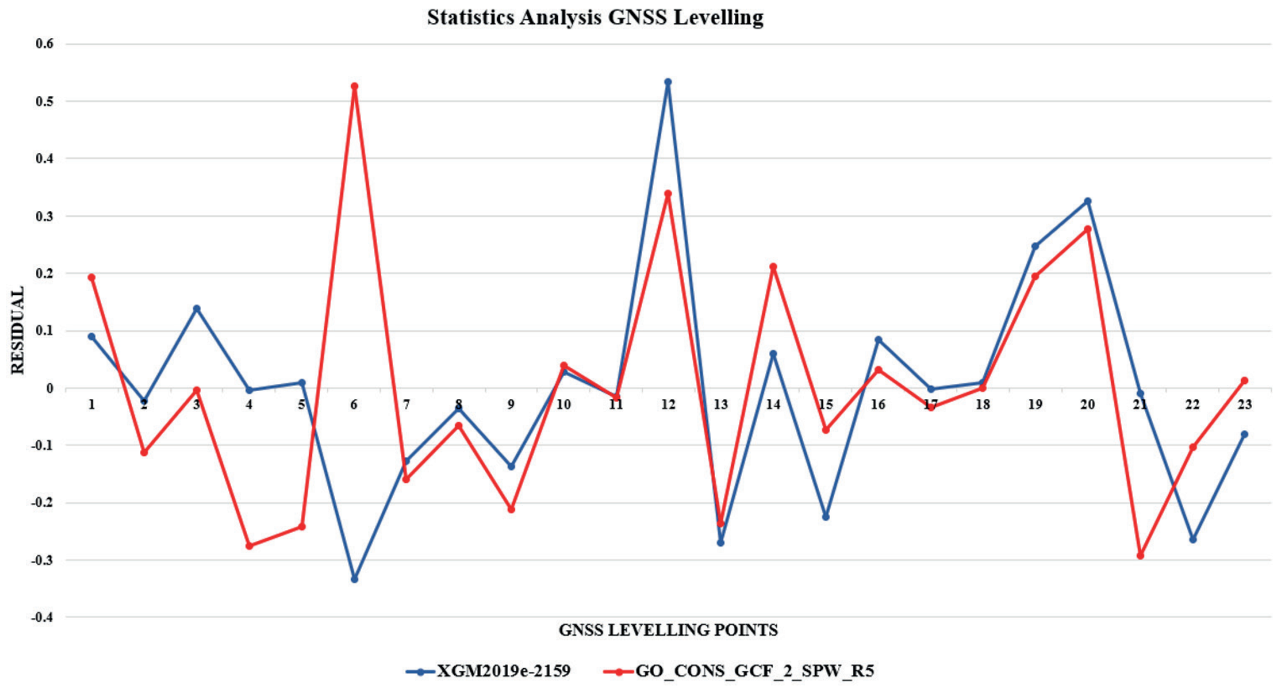
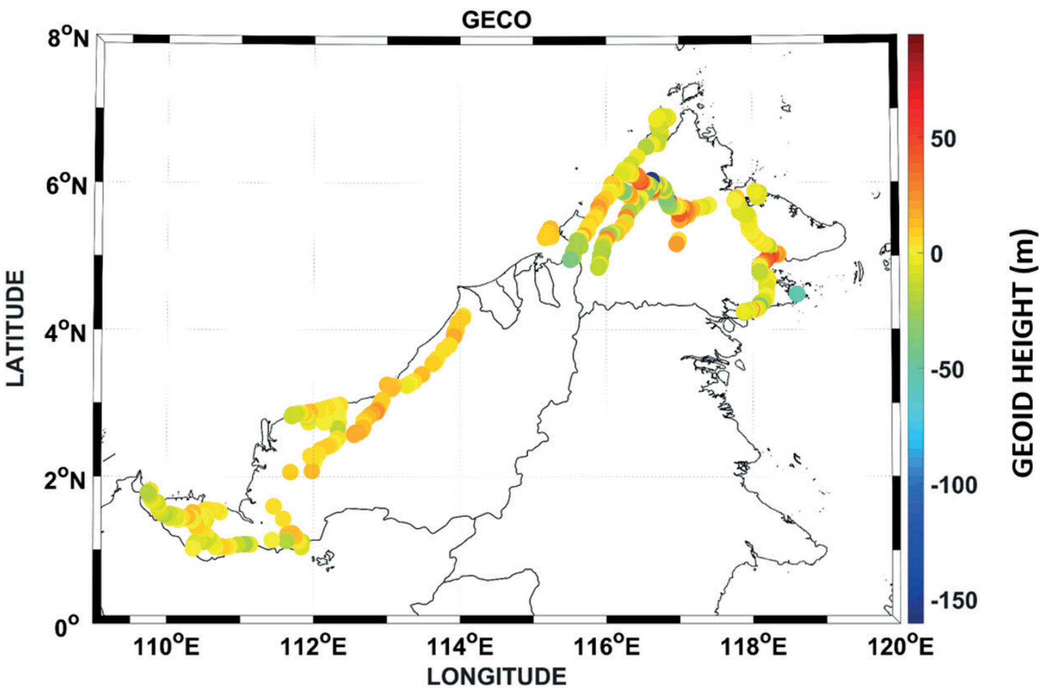


Fig. 6. Differences between GGMs and GNSS levelling over Sabah region

Table 3. Statistical analysis of the difference between GGMs and terrestrial gravity anomaly [unit:mGal]

GGM	Min	Max	Mean	RMSE
SGG-UGM-2	29.108	60.384	46.690	32.777
XGM2019e-2159	29.115	60.371	46.695	32.780
SGG-UGM-1	29.083	60.394	46.657	32.775
GECO	**29.112**	**60.372**	**46.669**	**32.760**
GO_CONS_GCF_2_TIM_R6E	29.065	60.597	46.530	32.760
GO_CONS_GCF_2_DIR_R5	**28.959**	**60.644**	**46.494**	**32.456**
GO_CONS_GCF_2_DIR_R6	28.993	60.577	46.496	35.754
GO_CONS_GCF_2_SPW_R4	29.106	60.779	46.661	32.800
GO_CONS_GCF_2_SPW_R5	28.786	60.469	46.505	32.761
GO_CONS_GCF_2_TIM_R5	28.964	60.613	46.492	32.759
GO_CONS_GCF_2_TIM_R6	29.064	60.600	46.530	32.760
GOGRA04S	28.678	60.896	46.493	32.779
GOSG01S	28.752	61.356	46.632	32.828
IfE_GOCE05s	28.958	60.811	46.478	32.779
ITU_GGC16	28.993	60.643	46.522	32.765
JYY_GOCE04S	28.675	60.899	46.488	32.779
Tongji-GMMG2021S	29.075	60.634	46.523	32.759
Tongji-Grace02k	29.132	60.698	46.510	32.903
Tongji-Grace02s	29.120	60.797	46.514	32.907



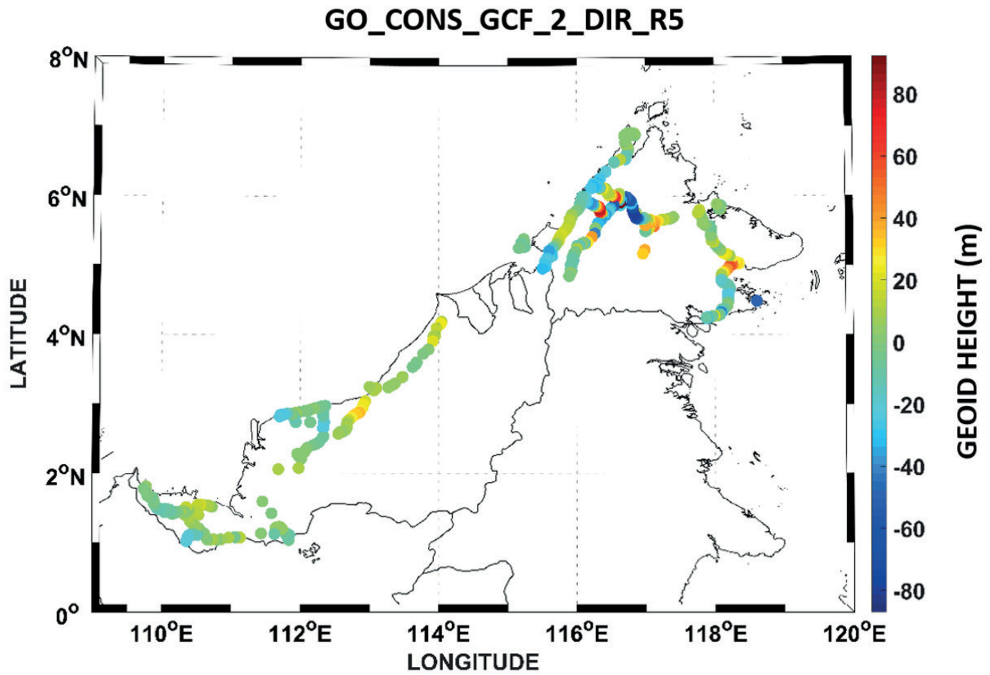


Fig. 7. Differences between (a) GECO GGM and (b) GO_CONS_GCF_2_DIR_R5 GGM with 680 terrestrial gravity anomalies

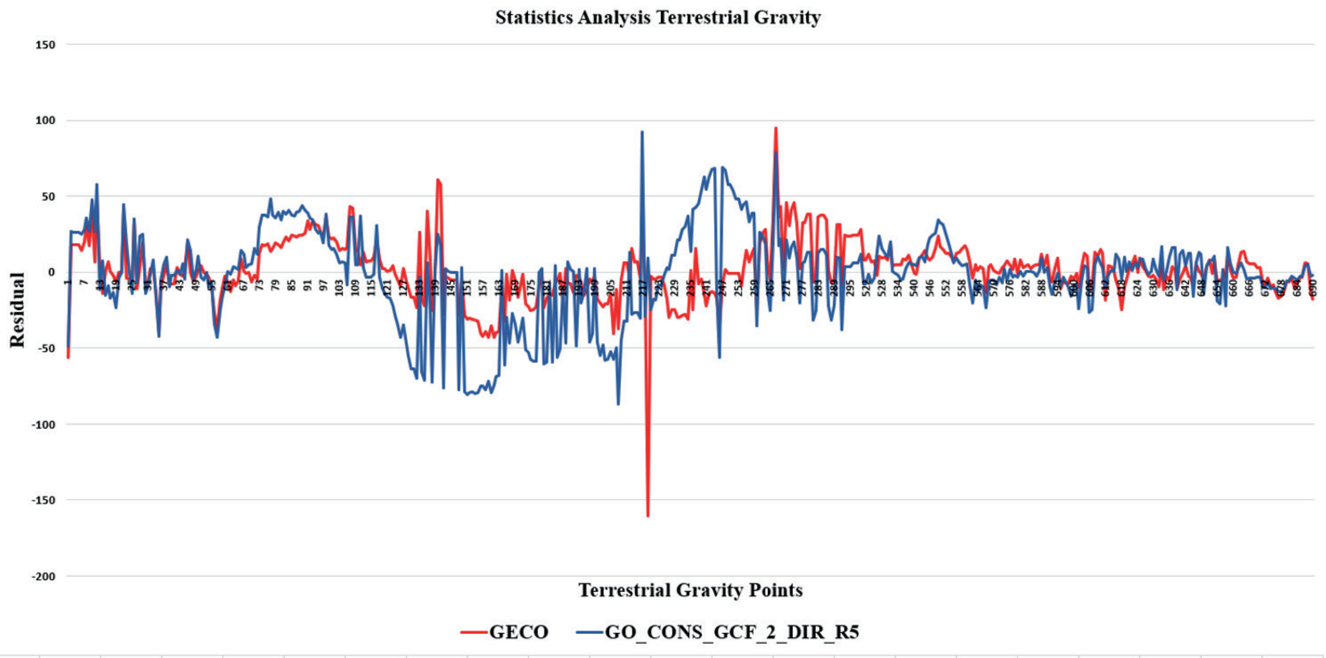


Fig. 8. Differences between two GGMs and terrestrial gravity anomalies over East Malaysia

GNSS leveling data. One of the key challenges identified is the uneven distribution of GNSS leveling points, which influences the reliability of models, particularly in inland mountainous areas. This uneven distribution directly affects the evaluation and validation of GGMs. Meanwhile, coastal and lowland regions, where infrastructure is more developed, provide better accessibility for setting up GNSS reference stations, ensuring more reliable and accurate measurements. This makes it easier to validate GGMs like GECO and GO_CONS_GCF_2_DIR_R5 in these areas. In contrast, the mountainous interior of East Malaysia, characterized by challenging terrain, sparse population, and limited infrastructure, has fewer GNSS points. This lack of data coverage limits the ability to properly assess the accuracy of the GGM models in these regions, contributing to the variability in performance among different GGMs. The results show that combined GGMs, which integrate data from multiple satellite missions, perform consistently across the region. Among the combined models, the GECO GGM showed the best fit with terrestrial gravity anomalies, achieving a mean error (ME) of 46.669 mGal and root mean square error (RMSE) of 32.760 mGal. However, the differences in RMSE values among the combined models were minimal, indicating stable performance across the set. For satellite-only GGMs, the GO_CONS_GCF_2_DIR_R5 model had the closest agreement with terrestrial gravity data, with an Mean of 46.494 mGal and RMSE of 32.456 mGal. Other satellite-only models, such as Tongji-Grace02s, displayed higher RMSE values, highlighting some variability in their accuracy. These findings suggest that satellite-only models can effectively capture large-scale gravity variations, but their precision may vary depending on the model used. Interestingly, the analysis reveals that combined GGMs perform better than satellite-only GGMs when evaluated with GNSS leveling data, indicating that integrating data from multiple sources improves overall reliability. In contrast, satellite-only GGMs align more closely with terrestrial gravity anomalies, suggesting they are better suited for detecting broad-scale gravity variations. In conclusion, GECO GGM is identified as the most suitable combined model, while GO_CONS_GCF_2_DIR_R5 performs best among satellite-only models. As shown in fig 8, the differences between GECO and terrestrial gravity anomalies range from 29.112 mGal to 60.372 mGal, and for GO_CONS_GCF_2_DIR_R5, from 28.959 mGal to -60.644 mGal. These findings highlight the importance of selecting appropriate GGMs based on the type of analysis and data available. While combined GGMs provide robust solutions across datasets, satellite-only models may offer better alignment with specific gravity measurements, contributing to more precise geoid model development for the region.

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